Investigating the potential impact of energy efficient measures for retrofitting existing UK hotels to reach the Nearly-Zero Energy Building (nZEB) standard.

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Abstract

The existing non-residential building stock can generally be considered energy inefficient. The ECUK 2017 report states that the final energy consumption for commercial buildings remained static. The 2010 recast Energy Performance Building Directive (EPBD) has set out a requirement for commercial and residential buildings to be nearly Zero Energy Buildings (nZEBs) by 2020. Despite this, within the UK a definition does not exist at the national level for commercial nZEBs (new or existing). This paper utilises the EU zebra2020 data tool to set a standard based on the existing UK nZEB commercial building stock. The aim of this paper is to investigate and assess the potential of various energy efficient measures (EEMs) and their contribution to reducing energy consumption, primary energy consumption (PEC), and CO_2 emissions whilst taking into consideration the energy and cost-savings of those measures. The analysis is carried out using Thermal Analysis Simulation software (Tas, Edsl). The model validation obtained a performance gap of less than 5%. The results show that it is possible to achieve the nZEB standard for older UK hotel buildings if several measures are implemented and the initial selection of EEMs is carefully investigated. Based on the results reaching the nZEB target should first take into consideration improving the building fabric and/or building envelope elements to lower the energy demand. Once the energy demand of the building is lowered the incorporation of a renewable/microgeneration system is essential to meeting the nZEB target.

Keywords: Nearly zero energy buildings; energy retrofit; energy simulations; historical building

List of Acronyms/Nomenclature	
ACH	Air changes per hour
CO_2	Carbon dioxide
CIBSE	Chartered Institute of Building Services Engineers
DSY	Design Summer Years
DHW	Domestic Hot Water
EDSL	Environmental Design Solutions
EPBD	Energy Performance Building Directive
EEMs	Energy Efficient Measures
HVAC	Heating, Ventilation, and Air Conditioning
MVHR	Mechanical Ventilation with Heat Recovery
NCM	National Calculation Methodology
nZEB	Nearly-Zero Energy Building
neZEH	Nearly-Zero Energy Hotel
PEC	Primary Energy Consumption
TAS	Thermal Analysis Simulation
TRY	Test Reference Years
U-value	Thermal Resistance.

1. Introduction

The fifth legally binding carbon budget (CB2; 2018-2022) which aims to reduce carbon emissions by at least 80% below 1990 levels, by 2050, was approved by the UK government during 2016 [Carbon Budget Order, 2016/*785*]. Commercial property account for 13% of the UK built environment, contribute to 10% of CO_2 emissions, and consume 7% of UK energy [PDR, 2017; DUKES, 2017]. Furthermore, the ECUK 2017 report states that the final energy consumption for the domestic sector has experienced a decrease from 2008 levels; meanwhile, for commercial buildings no changes were reported. Generally, the building sector is the largest consumer of energy across Europe and is responsible for 40% of total energy consumption and 36% of CO_2 emissions, meaning that it plays a vital role in reducing projected increases in energy consumption and carbon emissions in the coming years.

In tandem with the carbon budget, the recast 2010 Energy Performance Building Directive (EPBD) requires all new buildings (including buildings that will undergo renovations) to be Nearly Zero Energy Buildings (nZEBs) by 2020 [Directive 2010/31/EU]. nZEBs were described as "very high-performance buildings [where] the nearly zero of energy required should be covered by energy from renewable sources." Although the percentage of existing and new residential buildings being retrofitted and constructed significantly outweighs that of non-residential buildings, they consume considerably more energy in comparison. Despite this, many studies have only focussed on considering the retrofit of residential buildings. As a result, passive houses and net zero energy residential buildings have already been successfully implemented in across Europe; meanwhile the same progress has not been seen for non-residential buildings [Paoletti *et al.,* 2017].

A 2017 study which analysed 411 nZEBs across 17 EU countries (using the zebra2020 data tool) showed that renovated buildings represent just 19% of the sample and non-residential buildings only make up 36% of the sample [Paoletti *et al.,* 2017]. Those percentages further reflect the slow progress that is being made towards defining nZEB standards for non-residential buildings, and particularly for existing buildings. For most cities the number of existing buildings overshadows the possible number of new buildings; correspondingly, the potential impact of existing buildings, in terms of energy consumption reductions, outweighs that of new buildings.

A significant issue associated with the nZEB retrofit of existing non-residential buildings is the limited number and type of energy efficient measures (EEMs) that can be incorporated due to several reasons such as the regular technical installations on the roof; constant occupancy and use; unconventional frame type and existing materials; in addition, there is a need to maintain certain aesthetics depending on the building use. Furthermore, on average a residential building's energy demand can be easily met and offset with just renewable energy; meanwhile, commercial buildings can have up to five times the energy demand of a residential building. This coupled with the limitations discussed raises questions regarding the technical feasibility of nZEB retrofit for non-residential buildings.

Currently within the UK there have been no investigations carried out to examine whether it is feasible to retrofit historical buildings to reach the NZEB standard. This study therefore aims to investigate the potential for an existing 1860s UK hotel to reach the nZEB standard. The methodology adopted for this study involves several stages. Firstly, Thermal Analysis Software (Tas, Edsl) is utilised to provide an accurate prediction of the energy consumption, primary energy consumption (PEC), CO_2 emissions, building fabric and thermal performance of the building. The absence of an official definition for UK nZEBs means a new approach must be taken to come up with a definition that is both numerical and specific to UK commercial nZEBs. To ensure validity of the baseline model, the modelling results are compared to the actual data of the building which was gathered by the authors in collaboration with Hilton. Although this approach is time consuming in comparison to the typical methodology used across simulation studies (which usually involves validation of a reference model using a set database), it ensures that the study's outcomes are valid and applicable to other buildings of the same stock. Once the baseline model has been simulated and validated, the EEMs are individually simulated on the case study. Subsequently, the EEMs are combined to form sets of retrofit scenarios based on an iterative methodology, so that all the possible combinations of the selected EEMs are trialled.

2. Literature Review

Across Europe various studies have considered whole-building retrofit on existing/reference case studies to reach the nZEB standard. However, most of the current literature considers residential buildings, with very few studies focussing on non-residential buildings; particularly historical/older buildings which tend to be more challenging to retrofit. Loli and Bertolin (2018) highlighted the need to consider "minimal technical interventions" when retrofitting buildings of historical importance. Considering that Hilton Edinburgh Grosvenor is an 1860s building with a listed building consent requirement (i.e. it is of special architectural/ historical interest) it is essential that the retrofitting scenarios explored do not include redundant refurbishment of the building fabric. Meaning that where possible it would be best to work with the existing fabric or ensure that any improvement is justified in terms of the energy and cost-savings it has to offer and that it does not alter the current appearance of the building.

A similar notion is established from a study in Italy which explores whether the retrofitting of a historical educational building is feasible. Ascione *et al.* 2017, concluded that whilst significant energy, economic, and environmental savings are achievable; heritage buildings present more particularities and offer less flexibility regarding the type of energy-saving measures which can be incorporated. Correspondingly, the redesign of a rural building in a heritage site located in Italy to reach the nZEB standard found that 'invasive' measures could only be justified in the case of insulation due to the high energy savings achieved. The results also showed that the best performing solutions were those with "limited invasiveness" such as lighting [Cellura *et al.,* 2017].

As part of the European initiative 'Nearly Zero Energy Hotels' (neZEH) 16 hotels across Europe were provided technical assistance to undergo refurbishment and reach the NZE standard [Tsoutsos *et al.,* 2013; Tsoutsos et al., 2018]. Located in Rethymnon, Crete, Greece, the Ibiscos Garden hotel is one of the 16 pilot case studies aiming to reach the nZE standard [neZEH, 2017]. The initial implementation of solar thermal heating followed by an increase of 50 percent of its solar storage tank, means that all hot water consumption within the hotel is now met by renewable means. One of the interesting actions to be undertaken is the "energy upgrading of kitchen equipment" [Tassos, 2017]. According to 'Hotel Energy Solutions' (HES) preparing meals is one of the main energy consuming activities in a hotel after heating, including hot water, cooling, and, lighting [HES, 2011]. This is corroborated by the 2017 Hotel Data Conference, which presented that on average 'room heating/cooling and hot water' make up 63 percent of energy consumption, following this is 'kitchen' which makes up 11 percent of energy consumption [HNN, 2017]. Whilst it may seem difficult to control this type of energy consumption, the upgrading of the equipment used is a very simple yet effective way to reduce kitchen energy consumption. This highlights that the retrofitting process should not always necessarily include traditional upgrading of the building fabric.

The Alpine mountain refuge 'Schiestlhaus,' Hochschwabgruppe, Austria is one of the thirty case studies analysed by the 'International Energy Agency' (IEA) for their NZEB research [François et al., 2017]. Due to its unique location, particularly the high altitude, and its south facing orientation it is able to rely on solar thermal energy to heat water and a photovoltaic system to generate electricity. One of the simplest yet very effective measures incorporated is Greywater recycling. The specific system used by this hotel is 'Greywater Recycling On-Demand' as opposed to the batch system. This system is very compatible with hotels due to its space saving and fast payback period [Siobhan, 2016]. On average, this saves up to 24 percent of mains water each month. Once again this demonstrates that selection of the retrofitting strategy should be adapted to utilise and work with the existing building's characteristics.

A 2014 study analysed energy efficient measures to achieve the nZEB standard for office buildings for the Estonian climate. It was concluded that to achieve the nZEB standard the incorporation of a PV system is essential (Pikas, Thaified, Kurnitski, 2014]. Using an office building case study, Berggren *et al.,* (2013), analysed the feasibility of the Swedish nZEB definition. The simulations showed that the nZEB standard is achievable using existing technologies, however, it was noted that window U-value and peak load heating requirements were not reached. Another study presented the design process of an office building in Portugal. The study highlighted that to achieve nZEB performance, standard and innovative EEMs should be combined with renewable systems [Gonçalves *et al.,* 2010].

Regarding the implementation of non-residential nZEBs, several Member States have released a form of plan or definition to guide the progress towards achieving nZEBs. However, according to D'Agostino *et al.,* 2016 "many of the national plans have missing or vague information," with many definitions missing numerical targets. Moreover, many of those definitions have only focussed on establishing a standard for residential buildings; leading to negligible progress towards defining the nZEB standard for non-residential buildings. Generally, across Member States there is also a lack of explicit and detailed policies relating to nZEB refurbishment. Furthermore, many Member States tend to have a common nZEB definition for both new and retrofit nZEBs, however, it is important that they are differentiated due to the inherently distinct characteristics of new and existing buildings. Many of the works analysing progress on nZEB definitions have concluded that the absence of this differentiation remains a significant impediment [Marszal *et al.,* 2011; Sartori, Napolitano, and Voss, 2012; D'Agostino*,* 2015].

2.1. Defining the Non-residential nZEB standard

Finding a common definition for nZEBs on a European scale is an arduous task. This is because of the flexible outline of the recast EPBD which lacked numerical targets and allowed Member States to define their own standard. The rationale behind this was due to the differences between local climatic conditions, level of building technology, building traditions, and level of ambition. Accordingly, between European countries nZEB definitions vary significantly and are difficult or impossible to compare. Thus, it would not be ideal to apply nZEB definitions interchangeably across European countries.

Annex I of the EPBD states that "the energy performance of a building shall be expressed in a transparent manner and shall include an energy performance indicator and a numeric indicator of primary energy use, …". It also highlighted that whilst member states can use other indicators, they must not neglect setting a specific value for the PEC. Based on this, it has been recommended that the energy performance indicator should be stipulated as "energy needs for heating and cooling" [Kurnitski, 2013]. In essence this means that lowering the energy demand of the building is necessary. As for the primary energy use for this study, the total PEC is considered on an annual basis. Consequently, the main indicators to be used throughout the study to assess whether the building has reached the nZEB standard is the PEC and CO_2 emissions. As for the energy consumption although its results are investigated, it will not act as an indicator seeing as there is no specific requirement in the EU directive (and as a result in any of the currently available nZEB definitions) that require a specific energy consumption of the building.

Voss *et al* [2011] proposed one of the earliest definitions of net and nearly zero energy buildings whereby it was established that a net-ZEB should offset the energy demand for the grid by utilising renewable energy to meet the building's energy demands. Meanwhile with a nearly-ZEB the balance achieved between energy supplied by the grid and locally generated energy is not zero. The 'National Renewable Energy Laboratory' (NREL) developed one the most widely-used definitions of classifying nZEBs; whereby the building should generate an equal amount of energy as it uses on an annual basis by the use of on-site renewables. Costs and carbon emissions of the measures and retrofitting process should also be taken into account. The definition developed by the International Energy Agency (IEA) considers nZEBs as buildings which do not rely on any fossil fuels [Voss and Riley, 2009]. According to a Lewis (2009), the fundamental concept behind nZEBs is that the building should meet all its energy needs via low cost renewable energy sources (RES). Ideally, a nZEB therefore needs to have an annual energy use that balances with the generated renewable energy [Lewis, 2009; Marszal and Heiselberg, 2009].

Commercial definitions of nZEBs can be very limited, for instance, although it is recognised that an annual net/nearly-zero energy balance is not satisfactory as a standalone requirement to classify a building as nearly zero energy, many commercial definitions define them as such [Karsten *et al.,* 2010; Marszal and Heiselberg, 2009]. In certain cases, energy inefficient buildings have been considered nZEBs due to their use of a large number of renewables, whilst neglecting lowering the energy demand of the building, meaning the building is not a truly energy efficient building [Karsten *et al.,* 2010; Voss *et al.,* 2012]. Moreover, these definitions do not take into consideration the interaction of the building with energy grids; although this is a standard recognised requirement for a building to be classified as a NZEB. [Sartori *et al.,* 2010; Voss *et al.,* 2012; Marszal and

Heiselberg, 2009]. Accordingly, such definitions or classifications do not follow the basic guidelines of the EPBD and should not be solely relied upon to set the nZEB standard.

Looking at the currently available definitions across Europe, the RT2012 national law released in France stipulates a PEC of 110 kWh/m^2/yr or lower for new non-residential nZEBs [Roger *et al.,* 2013]. In comparison to this, Austria's OIB Directive 6 national law specifies a PEC of 170 kWh/m^2/yr or lower in non-residential nZEBs [AEA, 2010]. Meanwhile, in June 2015, Italy released the DM 20 national law which outlines a calculation method whereby the PEC of a nZEB should be calculated based on a reference building; it also presents "a minimum rate of renewables" to include heating, DHW, ventilation, lighting, cooling, and movement of people (lifts) for non-residential nZEBs [CAE, 2013]. The UK still has not released an official definition for non-residential nZEBs.

A possible solution to defining the nZEB standard for a UK commercial building where there is a lack of official definition would be to utilise the tools developed by the zebra2020 project. The EU zebra2020 project was launched in 2014 with the purpose of presenting nZEB building indicators and establishing strategies to resolve barriers to reaching the nZEB standard across Europe. The project synthesised data from numerous nZEB case studies which allowed a quantitative and qualitative analysis on the performance and key characteristics of successful nZEBs across Europe to be carried out. The tool is one of the few databases that cover 90% of the existing nZE building stock.

The tool is divided into three sub-tools. In more detail, the first part of the tool is called the 'Data Tool,' and it provides a summary of the existing building stock by country and aims to "overcome data gaps" by offering detailed information regarding the transition towards nZEBs. The second part of the tool is the 'nZEB Tracker' which offers building information for existing successful nZEB case studies and their relevant indicators such as the primary energy performance, passive and active energy efficient solutions and types of renewables utilised. The tool separates those indicators for residential and non-residential buildings and the information is presented by country, therefore, the tools shall be used to aggregate a definition with numerical targets specific to UK non-residential nZEBs [Table 1]. Table 2 is showing the list of the possible EEMs which are initially implemented on the building. The main potential areas of retrofit were categorised into insulation, glazing, lighting, HVAC/DHW and microgeneration systems. The EEMs were then selected based on their applicability to the building and placed into one of the categories. Where applicable various sizes of one measure (e.g. 100mm, 120mm… sheep's' wool] were trialled to examine which size offers optimum results.

Table 1: Building fabric, energy consumption, primary energy consumption and carbon emissions of the case-study building as obtained from TAS against the nZEB target

	nZEB Target	Case-study
Wall (W/m²K)	0.11	0.35
Floor (W/m²K)	0.10	0.25
Roof (W/m²K)	0.15	0.25
Windows (W/m²K)	0.92	2.2
Air permeability rate (m³/h/m² @50Pa)	2.00	10.0
Energy Consumption (kWh/m²)	80-95	289.79
Primary Energy Consumption (kWh/m²)	125 (OR at least 60% reduction in PEC)	378.21
Carbon Emissions (Kg/CO_2/m²)	At least 50% reduction in annual Carbon Emissions	95.6

Table 2: Summary of selected EEMs

	Design Measure	Acronym
Insulation (EEMs 1-12)	100-200mm Sheep's Wool	SW
	100-200mm Cellulose	CE
Glazing (EEMs 13-14)	Triple Glazing, 36 mm Argon filled, Low-e	TGA
	Triple Glazing, 36 mm Krypton filled, Low-e	TGK
Lighting (EEMs 15-16)	LED + Auto presence detection	LED+A
	CFL + Auto Presence detection	CDL+A
HVAC & DHW (EEMs 17-38)	Automatic Thermostat controlled direct gas fired Boiler	ATB
	Programmable Thermostat direct gas fired Boiler	PTB

	Mechanical Ventilation with heat recovery	MVHRV
	Mechanical Ventilation with energy recovery ventilator	MVERV
	60-200kW Air Source heat pump	ASHP
	30-130 kW_{th} Solar Water Heating	SWH
	50-250kW High Efficiency Biomass Boiler	BB
Microgeneration systems (EEMs 39-50)	100-350kWe Combined Heat and Power	CHP
	100-350kWe Combined Cooling Heating and Power	CCHP

3. Methodology

3.1. Case Study

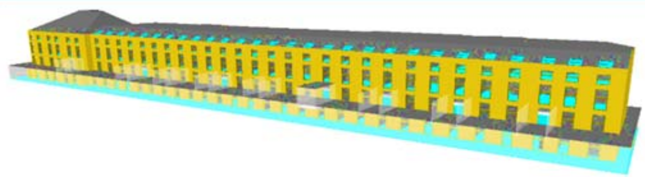
The case study selected is Hilton Edinburgh Grosvenor hotel located in Scotland, Edinburgh and constructed in the 1860s. It is spread over two separate buildings, as shown in Figure 1a and 1b, and has a total floor area of 10,304m^2. The type of construction is historical stone wall. Heating in the hotel rooms is met by a series of gas fired boilers. Overall, the hotel has 19 split AC/VRF systems serving the meeting rooms, back of house offices, server rooms, and front of house areas. Certain public areas of the hotel are also fitted with LED lighting. Not uncommon to older UK buildings, the type of glazing originally was single glazed sash windows that have now been upgraded to double glazing.

Building modelling and simulation software TAS is used to predict energy performance, baseline and mitigated CO_2 emissions, thermal performance and therefore occupant comfort. Initially, the model created on TAS is a replica of the existing state of the building. Thus, the initially generated energy model will act as the reference point for improvements and is defined as the 'baseline model.' The total energy consumption value obtained from TAS considers heating, cooling, auxiliary, lighting, domestic hot water (DHW) and is the net of any electrical energy displaced by renewable/microgeneration systems, if applicable. The PEC is the amount of primary energy consumed in order to meet the building's energy demand (heating, cooling, DHW, lighting, and auxiliaries) and is also the net of any electrical energy displaced by C/CHP generators, if applicable.

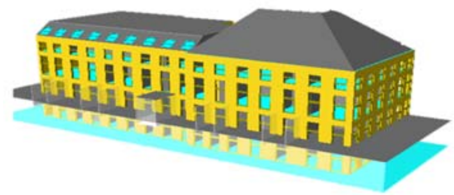
The type of weather file selected for carrying out the analysis is the Edinburgh Test Reference Year (TRY). This is selected because the Design Summer Year (DSY) weather file is suitable for overheating analysis. Meanwhile, the TRY is suitable for "energy analysis and compliance with the UK Building Regulations (Part L)" [Cibse, 2009a; Eames, Ramallo-G, and Wood 2016; Mylona 2017; Cibse 2017].

Refer to Amaoko-Attah and B-Jahromi (2014) for detailed description of the modelling process on TAS.

a) typical floor plan of (i) the main building (ii) town-house | b) Ordnance survey sitemap of the hotel buildings



c) 3D model of the main building

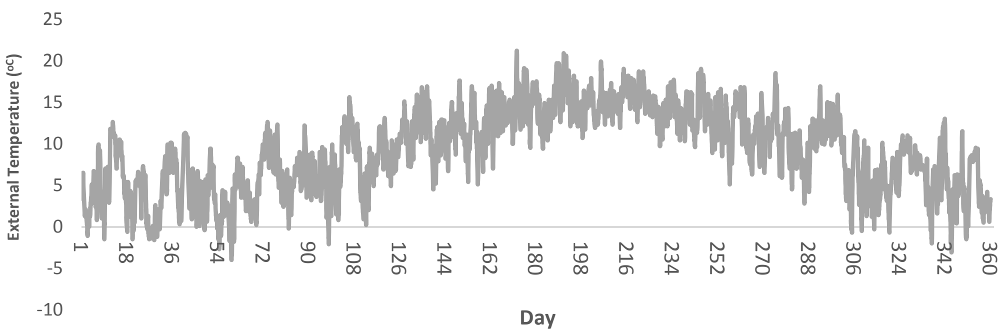


d) 3D model of the town-house

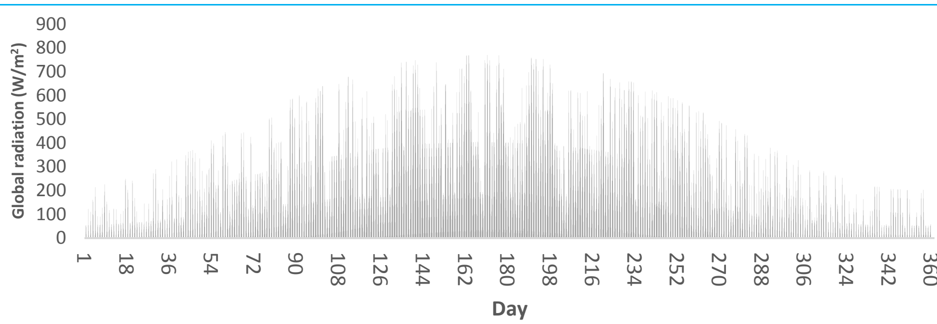
Figure 1: Typical floor plan, OS sitemap, and TAS 3D Model of the hotel

3.2. Modelling Assumptions

1. It is assumed that the hotel is occupied 24 hours, seven days a week. This is selected based on average occupancy patterns in the hotel.
2. The National Calculation Method (NCM) database is used to represent all zones, as shown in Table 3. It is assumed that these conditions are the actual current conditions of the hotel.
3. Fully adopting the CIBSE TRY weather files without any alterations and assuming that they are valid and relevant to the microclimate of Edinburgh.
4. Figure 2 shows the external temperature and global solar radiation, heating and cooling degree day data and the 3D visualisation of the resultant temperature on the building case study.



(a)



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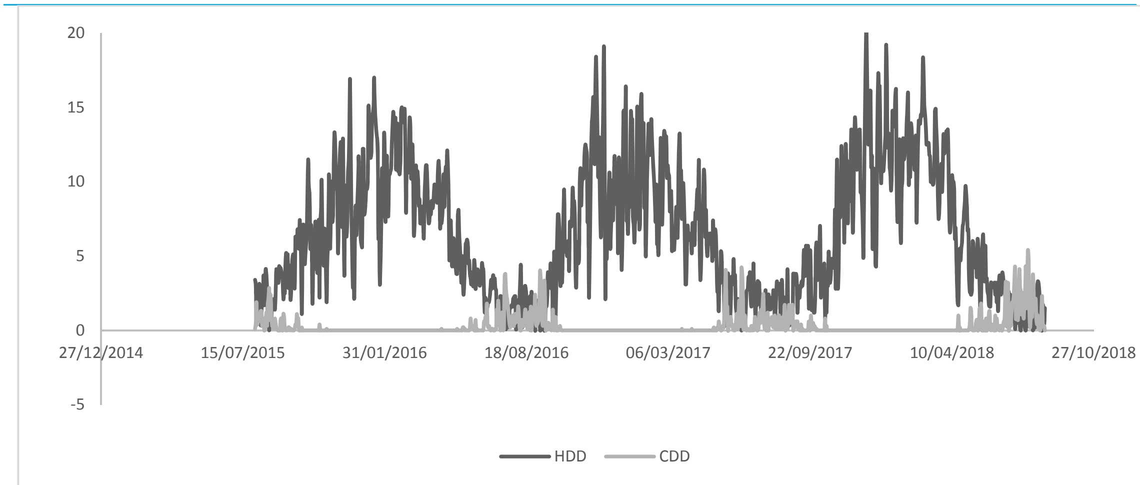

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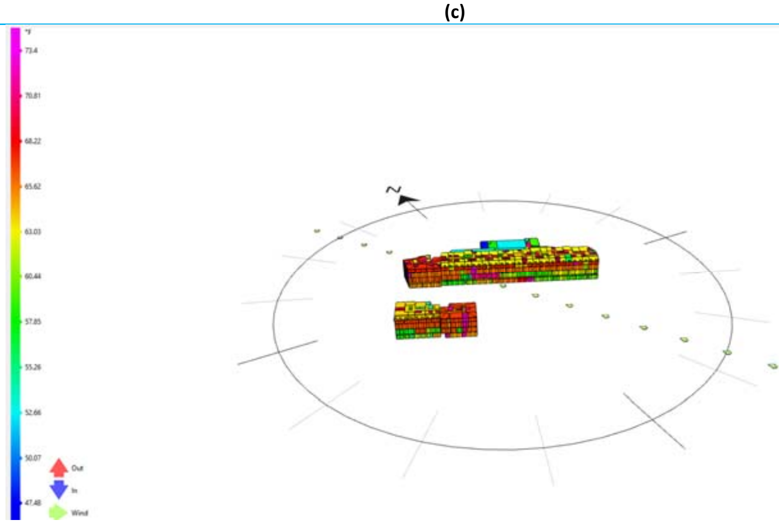


(d)

Figure 2: (a) External temperature and (b) global solar radiation data (c) Heating and Cooling degree data, (d) 3D visualisation of the resultant temperature used for the building case study

Table 3. Summary of modelling and simulation assumptions

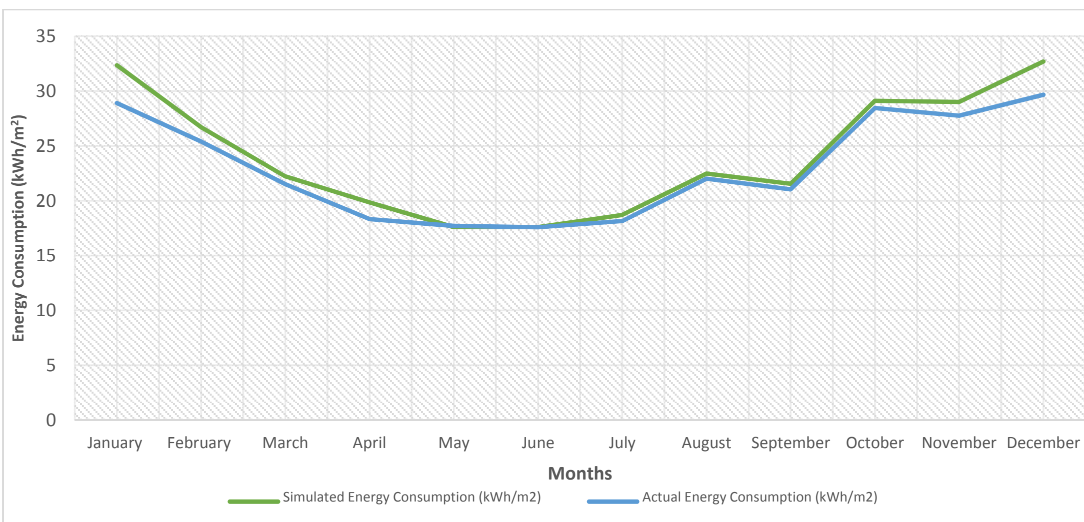
Construction database	NCM Construction -v5.2.tcd
Zone - occupancy levels, people density, lux level	Car Park - 0.0059 person/m², 100 lux Bedroom - 0.094 person/m², 100 lux Toilet - 0.1188 person/m², 200 lux Plant Room- 0.11 person/m², 50 lux Changing Room- 0.112 person/m², 100 lux Reception - 0.105 person/m², 200 lux Hall - 0.183 person/m², 300 lux Food prep/ kitchen- 0.108 person/m², 500 lux Eat/Drink area - 0.2 person/m², 150 lux Office - 0.106 person/m², 400 lux Meeting Room - 0.094 person/m², 100 lux Circulation - 0.115 person/m², 100 lux Store- 0.11 person/m², 50 lux Laundry - 0.12 person/m², 300 lux
Building Fabric – Calculated area weighted average U-values	Wall – 0.35 W/m²K Floor – 0.25 W/m²K Roof – 0.25 W/m²K Window – 2.2 W/m²K
Fuel Source	Natural Gas – CO_2 Factor – 0.198 Kg/kWh Grid Electricity - CO_2 Factor – 0.4121 Kg/kWh

Performance efficiency used in modelling	ASHP – 95% efficient [using current SAP default] CHP – 37% elec. efficiency & 47% heat efficiency [as confirmed by CHPA] CCHP – 17% elec. efficiency & 60% heat efficiency [adjusted data from CHPA] Biomass Boiler – 85% efficient MVHR -Specific fan power = 0.5 & heat recover efficiency = 90% SWH – Zero loss collector efficiency = 0.81; heat loss coefficient = 3.9 [as confirmed by REA]
Orientation	55.9470° N; 3.2170° W; +0.0 UTC
Air Permeability	10 $m^3/h/m^2$ @50Pa
Infiltration	0.500 ACH
Weather data	TRY (CIBSE) for Scotland, Edinburgh. Includes: Global solar radiation, Relative Humidity, Wind Speed and Wind direction, Dry Bulb Temperature, Diffuse Solar radiation, and Cloud Cover.

4. Results and Discussion

4.1. Baseline Model Validation

To evaluate the impact of the measures to be incorporated on the case-study building, the initial simulation is conducted to reflect the actual current state of the hotel without any alterations. To validate the simulation results obtained from TAS the simulated energy consumption value is compared with the actual building's energy consumption. The simulation model was thoroughly populated to reproduce all the characteristics and systems of the building as built. Looking at Figure 3, the difference between actual energy consumption and simulated energy consumption is 4.60%. Even though this 4.60% is an overestimation of the actual energy consumption of the building, it should be noted that the accuracy of the simulation results depends on factors such as the weather data used for the simulation which should ideally replicate the microclimate of the building's location and actual occupancy rates [Rotimi *et al.,* 2017]. However, this is challenging to achieve and can lead to the variation between simulated and actual energy consumption. Furthermore, the building is constructed from stone walls and there is evidence from various studies that historical stone walls have a better thermal performance than expected and obtained from standard calculations and therefore computational modelling [Currie, Williamson, and Stinson, 2013; Li *et al.,* 2014; Lucchi, 2017; Mantesi *et al.,* 2018]. This is because whilst simulation models/ standard calculations consider stone walls as monolithic, in reality, the proportion of stone, mortar, and air gaps varies which in turn has an effect on the overall simulated building energy consumption.



$$Percentage\ Error: \frac{289.79 - 276.45}{289.79} x100 = 4.60 \ldots \%$$

Figure 3: Simulated monthly energy consumption against actual building energy consumption and their percentage difference

4.2. Suitability of individual EEMs

Figure 4a shows the energy consumption reduction contribution of each measure individually implemented on the case-study building in comparison to the 'baseline' energy consumption and how close this reduction is to the nZEB target. Looking at Figure 4a it can be observed that certain groups of measures offer a significant contribution to the reduction of energy consumption in comparison to other groups and for certain groups of measures, such as the microgeneration systems, the energy consumption increases.

However, this is not a true reflection of the contribution these systems have to offer. Figure 4b illustrates the significant reduction in PEC reduction that is achieved with the CHP and CCHP systems. Although only one measure is simulated on the building, the PEC is reduced by an average of 50% and 55% with CHP and CCHP, respectively, meaning that it almost reaches the nZEB target's stipulated 60% reduction in PEC. Similarly, all the differently sized CHP and CCHP units offered the largest contribution to the reduction of CO_2 emissions.

Figure 4d represents the energy savings against the cost savings of the EEMs and shows that generally the energy and cost savings are the lowest for insulation, lighting and glazing. For each of the EEMs the savings in energy are calculated by evaluating the difference in energy consumption with the EEMs and the baseline energy consumption. The annual electricity and gas cost savings are obtained by multiplying the consumption savings with the corresponding fuel price which is 10.30 pence/kWh for electricity and 3.50 pence/kWh for gas. The total of these savings is expressed relative to the baseline model as presented in figure 4d.

For most measures the energy and cost savings are positively correlated. Thus, measures with higher energy savings also have high cost-savings and vice versa. However, this is not the case for all the measures; for instance, certain measures had significant energy savings, yet their cost-savings were minor in comparison. Examples of this included the biomass boiler and solar water heating (SWH). On the other hand, some measures had very little energy savings in comparison to their cost-savings, as in the case of mechanical ventilation. Numerous studies have demonstrated that generally EEMs should be selected based on a balance of the energy and cost-savings [Gonçalves *et al.,* 2010; Congedo *et al.,* 2016; Ascione *et al.,* 2017; Salem *et al.,* 2018]. The comparison illustrated by figure 4d therefore provides an overview regarding which EEMs should be selected to create the retrofit scenarios and which ones should be avoided. It was also highlighted that it is possible to achieve similar energy savings for lower investment costs and higher cost-savings. For example, the energy consumption reduction and energy savings with lighting in comparison to glazing is ±5% (i.e. very similar), however, the difference between their capital cost is a substantial 80% and most importantly lighting had higher cost-savings. Nevertheless, one should note that this is site-dependent seeing as lighting affects power consumption which is traditionally more expensive, meanwhile, glazing affects heating/cooling which combined may have a lower unit cost as fuel is typically cheaper. However, if an electrically heated site is considered, then the difference in cost-savings may not be as significant.

Because of the hotel's heritage value/significance the insulation measures are simulated as internal insulation. Despite this, it is essential that the applied insulation still demonstrates effective improvements in energy performance and value for money. The two types of insulation materials initially selected complement the existing hygrothermal behaviour of the building; therefore, the risk of interstitial condensation (which can pose health problems for occupants and damage the building fabric) is avoided. Between sheep's wool and cellulose insulation, the CO_2 emissions reduction difference were negligible, although cellulose's performance was higher by an average of 5%. The energy and cost savings of cellulose insulation, however, were higher by an average of 15% in comparison to sheep wool insulation. Therefore, based on the simulation results, the 160mm cellulose should be selected to make-up the retrofit scenarios because any further increase in thickness will not have significant/additional benefits.

The existing glazing throughout the hotel is double-glazed sash windows. Although it is not provided by all suppliers and can be costly, triple glazed sash windows should still be considered, particularly with recent bouts of harsher weather in the UK. They do have extremely long payback periods (30+ years) and small energy and cost-savings despite being one of the costliest EEMs. Therefore, in real life application the final decision regarding the selection of double or triple glazing will depend on several factors because whilst the U-value target may not be reached, the energy consumption, CO_2 emissions, and PEC will not be largely affected. Furthermore, the energy performance of the hotel with insulation implemented outperformed the energy performance with glazing. For example, the average energy consumption reduction with triple glazing and insulation was 7% and 13%, respectively. This suggests that improving the insulation for this building works better to lower the energy demand in comparison to improving the glazing. This is particularly true due to the existing double-glazed windows. If double-glazing was not in-use already then improving the glazing to triple glazing would have contributed to a greater reduction in energy consumption.

Furthermore, studies have shown that nZEB u-value targets are not always technically attainable or cost-effective at all particularly where double glazing is already in place [Berggren *et al.,* 2013]. However, because the nZEB U-value target for windows is achievable if triple glazing is incorporated, for the purpose of this study triple glazed windows are included in the retrofit scenarios. Finally, although krypton filled triple glazing performed better in comparison to argon filled triple glazing, the difference, as seen by figures 3a, b, and d is not significant enough to justify the higher capital cost associated with krypton filled triple glazing.

Incorporating insulation and triple glazing means the building is now very airtight and that mechanical ventilation is necessary to avoid poor air quality. Based on the results it is clear that mechanical ventilation systems have the potential to reduce space heating demand. Although an energy-recovery ventilator (MVERV) generally provides better humidity control than a heat-recovery ventilator (MVHRV), the energy performance of the building with MVHRV surpasses the performance with MVERV. The energy consumption reduction was 18.82% with MVHRV and 10.34% with MVERV and the CO_2 reductions with MVHRV was 9.20% higher in comparison to MVERV. Similarly, the energy and cost-savings were on average 10% higher with MVHRV.

Currently LED lighting is being used in some public areas of the hotel. Although the auto-presence detection can only be used in certain public areas of hotels to ensure occupant comfort, the trialled simulation with LED and CFL lighting and auto-presence detection showed reductions in energy consumption, CO_2 emissions, and energy and cost-savings that are similar to costlier measures such as insulation and glazing, as discussed previously. However, looking at figures 3a, b, and d it can be seen that LED outperforms CFL. On average LED had energy and cost-savings that were 10% higher in comparison to CFL.

The simulations showed that improving the existing boilers to being automatic/programmable controlled thermostat boilers (ATB/PTB) has the potential to offer significant improvements in the energy performance of the hotel. Looking at the results it is clear that implementing heating control systems has the potential to substantially reduce energy consumption and CO_2 emissions whilst achieving high energy and cost-savings. In addition, heating controls are inexpensive relative to the contributions they offer and are known to have short payback periods as long as they are correctly utilised [MBS, 2018]. The automatic thermostat gas fired boiler contributed to a 27.36% reduction in energy consumption and a 14% reduction for CO_2 emissions. The overall energy and cost-savings of the automatic thermostat-controlled gas fired boiler was higher by an average of 12% in comparison to the programmable thermostat-controlled gas fired boiler.

Although the air source heat pump (ASHP), SWH, and the biomass boiler measures contributed to some of the largest reductions in energy consumption and carbon emissions their cost-savings were significantly lower in comparison to their energy-savings as illustrated by figure 3d. Therefore, this suggests that their incorporation as nZEB retrofit measures for this building is not suitable and it will not be very energy or cost-efficient. The implementation of heat pumps for the entire hotel also needs careful consideration because the extra electricity consumption associated with this measure can easily outweigh gas consumption savings. Furthermore, when the energy and cost-savings of those measures are compared with those of the microgeneration systems, it is apparent that implementing a microgeneration system is the most advantageous solution.

As discussed earlier, because majority of energy demand within the building is heating demand with moderate cooling demand during some of the hotter months, the incorporation of a CCHP unit is not a suitable solution for this hotel [Maria, Jose, and Eva 2017; Salem *et al.,* 2018]. Instead, a CHP is more compatible with the heating/cooling demands of this building and should therefore be used for the retrofit scenarios.

Overall, the implementation of certain measures alone can almost reduce the energy consumption, CO_2, and PEC to the required nZEB target. However, looking at the figure those are typically measures that are oversized for the building's energy requirements. Most importantly, none of those measures were able to completely reduce any of the indicators to meet the required target. Thus, initially implementing the measures separately on the building, via simulation, highlights that to reach the nZEB standard several measures must be implemented together. In addition, nZEBs are intended to be 'truly' energy efficient buildings. Meaning that rather than just meeting the near-zero balance, it is vital that the energy efficiency of the building is improved, firstly, to lower the energy demand of the building; as opposed to implementing an oversized renewable/microgeneration system to meet and offset the existing energy demand. This is in consonance with the initial generic definition outlined by the EPBD [recast].

The next phase of analysis involves systematically implementing different combinations of EEMs until the nZEB target is reached. The measures are combined initially as sets of 2 and 3 combinations until all the possible different combinations of measures have been explored to see how many EEMs are required meet the nZEB target and which combination of EEMs perform well together. Investigating the combination of EEMs in this way will also offer valuable insight regarding whether the number or type of measures combined has a more prominent influence on improving the energy performance of the building and meeting the nZEB target. Based on the above results the selected EEMs have been altered and table 4 is showing the summary of the final selected EEMs.

Table 4: Summary of final selected EEMs

EEMs	Design Measure	Acronym
Insulation	160mm Cellulose	CE
Glazing	Triple Glazing, 36 mm Argon filled, Low-e	TGA
Lighting	LED + Auto presence detection	LED+A
HVAC & DHW	Automatic Thermostat controlled direct gas fired Boiler	ATB
	Mechanical Ventilation with heat recovery	MVHRV
Microgeneration	200kWe Combined Heat and Power	CHP

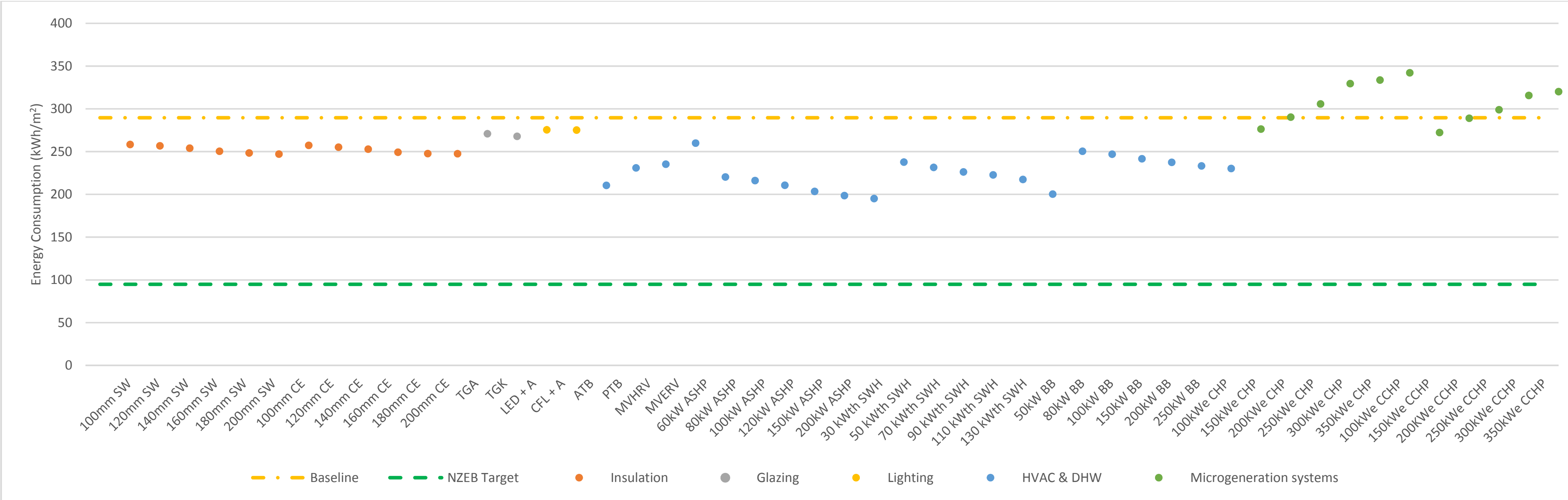


Figure 4a: Energy consumption with implemented measures

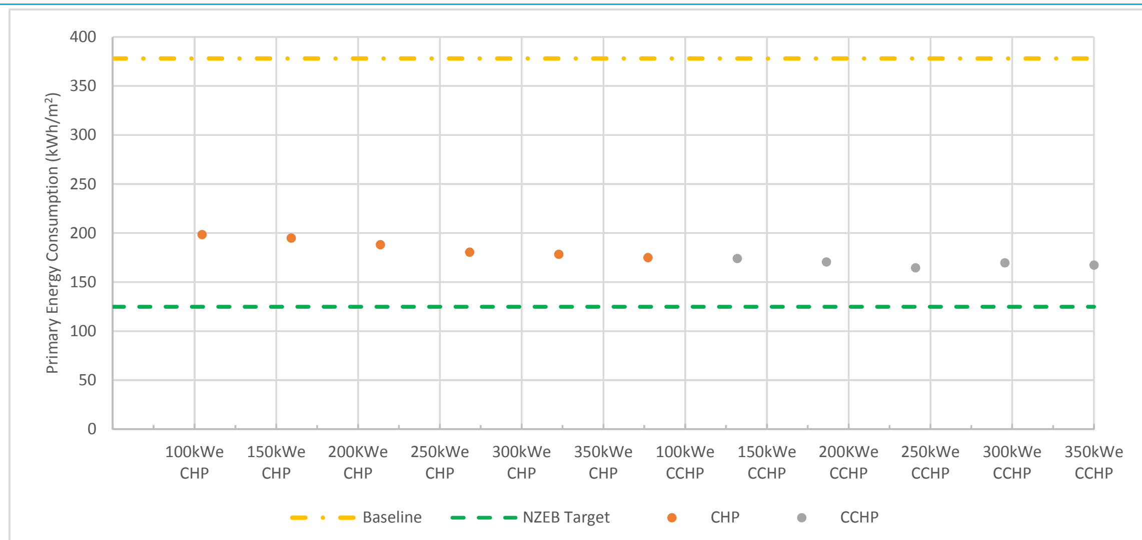


Figure 4b: Primary energy consumption of baseline model and with CHP and CCHP

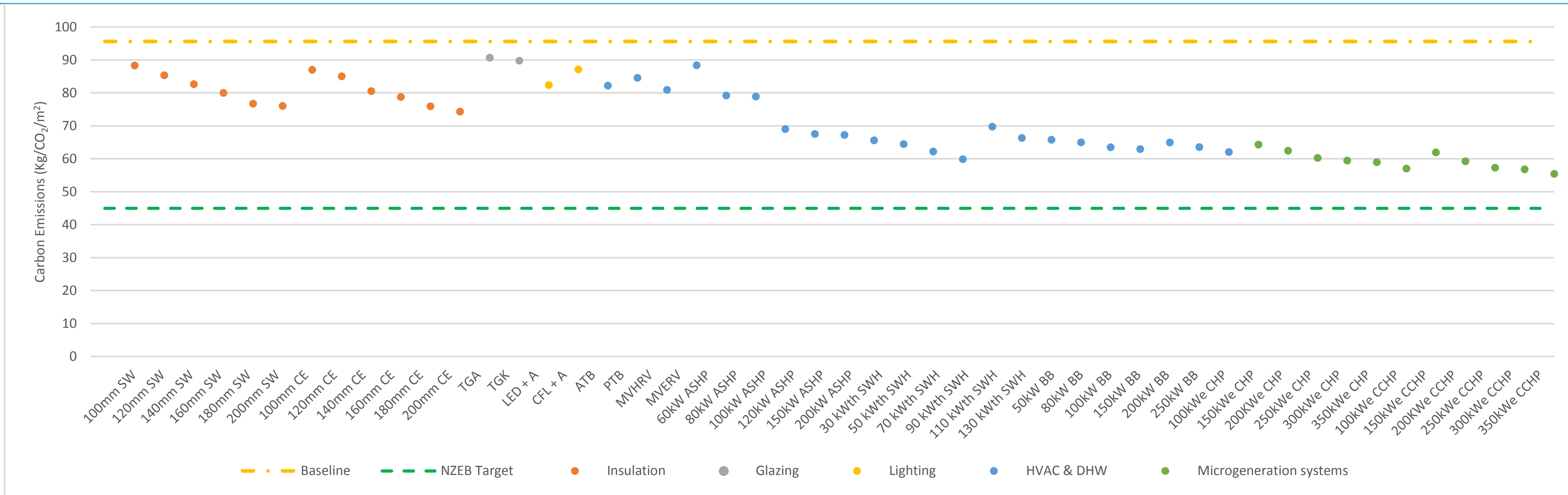


Figure 4c: Carbon emissions with implemented measures

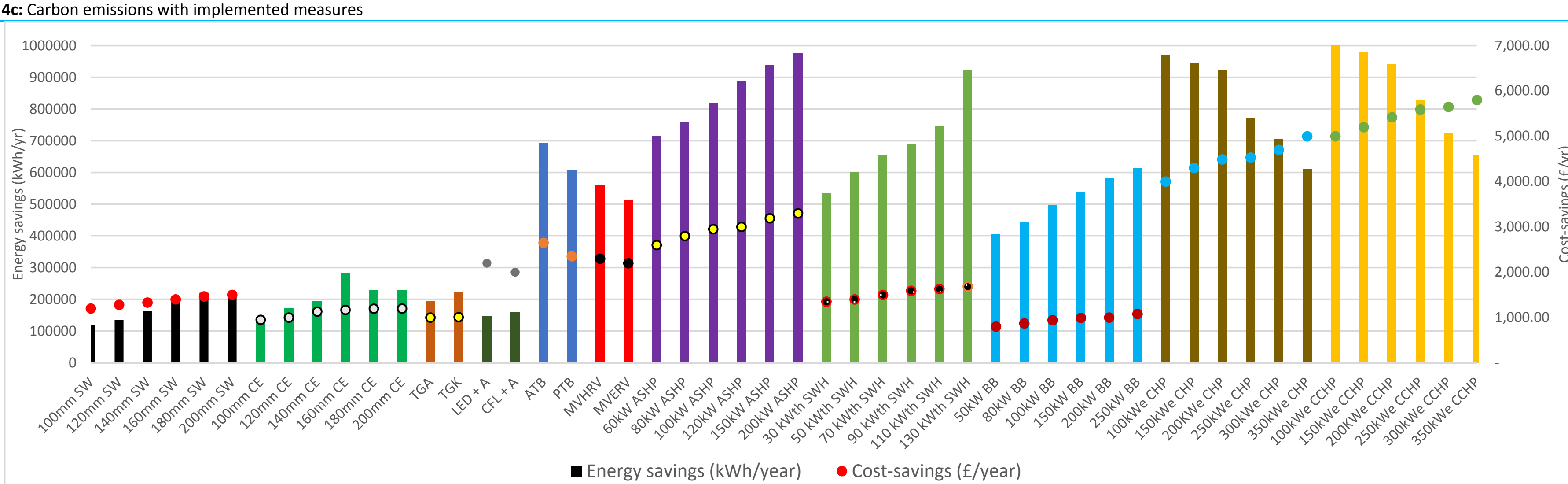


Figure 4d: Energy savings against cost-savings

Figure 4: Energy consumption, PEC, and carbon emissions of the case-study with individually implemented measures

4.3. Combined EEMs: investigation of nZEB feasibility

Figures 5-8 present the energy consumption, carbon emissions, and PEC reductions achieved with a combination of 2, 3, 4 and finally all possible combinations of the EEMs in comparison to the baseline model and the nZEB target. When evaluating the reductions achieved with the different combinations of EEMs, some issues are highlighted. Firstly, achieving the nZEB target for energy consumption with a CHP unit is not possible even when other measures are incorporated; meanwhile, the PEC and CO_2 emissions target is easily achieved with just CHP and three additional measures. Per EPBD guidelines the nZEB definitions that have been released across Europe have only focussed on setting the PEC as the main indicator for residential and commercial nZEBs. Correspondingly, across the literature, nZEB retrofit studies have also focussed on lowering the PEC of a case-study building to meet their respective targets, as discussed earlier. Therefore, not achieving the nZEB target for energy consumption due to the incorporation of CHP should not undermine its benefits and main advantage: drastically lowering the PEC. However, where an official definition is released, and it stipulates a certain level for energy consumption, then a renewable measure such as the SWH would have been a viable option to lower and meet the target despite the lower cost-savings to be achieved with this option. Therefore, the results suggest that to achieve the nZEB target a renewable/microgeneration system is essential. Even when a combination of insulation, glazing, lighting, and mechanical ventilation was implemented on the building it was not able to lower any of the indicators to the required target. This denotes that to meet the nZEB target a 'main' renewable/microgeneration energy saving measure combined with three additional measures should be implemented.

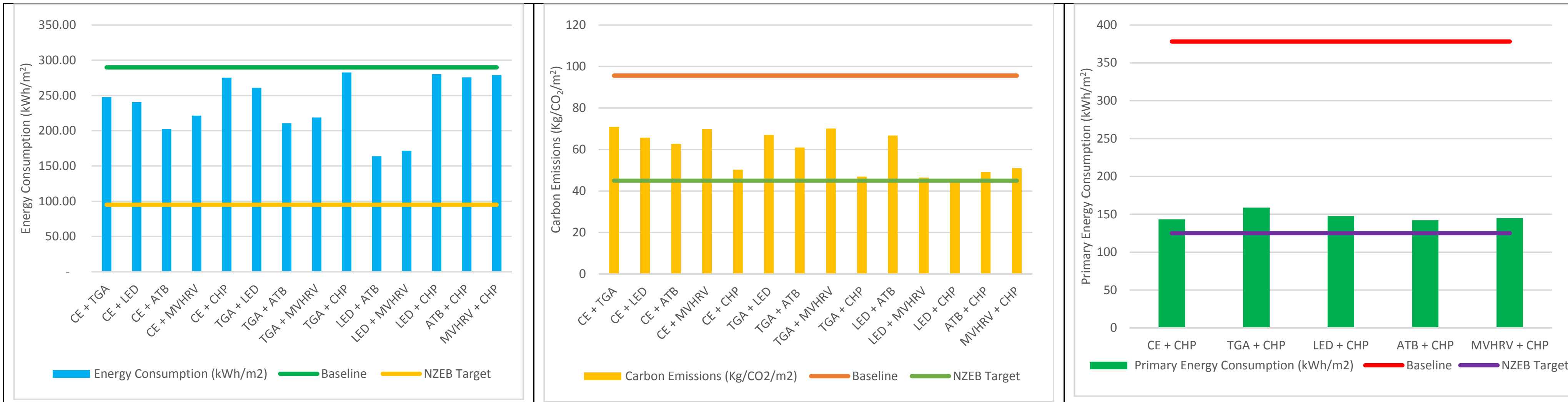
The main conclusion to be drawn from figure 5 is that the nZEB target is not achievable just by incorporating two EEMs. A combination of CHP and LED managed to reduce the CO_2 emissions to just meet the target and CHP and ATB resulted in the largest reduction in PEC. Combining insulation and glazing resulted in the smallest reductions for all indicators, making it the least favourable combination. On the other hand, the combination of LED and ATB resulted in the best average savings across the indicators.

Similarly, a combination of three measures does not meet the nZEB target for energy consumption or PEC and the CO_2 emissions target is only achieved when CHP is one of the EEMs being trialled as shown by figure 6. Implementing lighting, a HVAC/DHW measure, and CHP together contributed to the largest reductions for the indicators. Meanwhile, combining insulation, glazing, and lighting was the least favourable combination. It was also observed that a combination of insulation or glazing separately with 2 other EEMs outperformed the combination of insulation, glazing, and any other measure.

Figure 7 highlights that combining four EEMs is sufficient to reduce the CO_2 emissions and PEC to meet the nZEB target; however, once again the incorporation of CHP is necessary. The combinations of EEMs which did not include CHP performed best at reducing the energy consumption. Nevertheless, as discussed earlier because nZEB targets focus on reducing the PEC and CO_2 emissions to a certain level using these two indicators as the criterion as to whether the building met the nZEB target is satisfactory. It was apparent that the combinations of EEMs with insulation outperformed the exact same combinations but with glazing incorporated instead. Therefore, the incorporation of insulation, lighting, HVAC/DHW, and CHP offered the biggest reductions which is in consonance with the results obtained from figure 6.

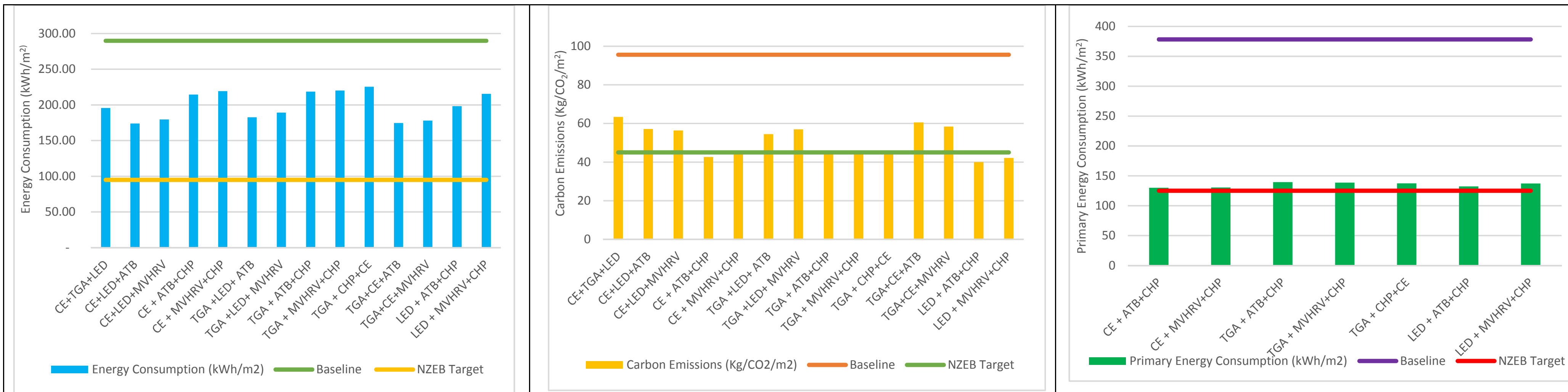
Implementing all the different combination of EEMs together on the building did not lead to additional significant savings in any of the three indicators as shown by figure 8. In fact, the PEC and CO_2 emission reductions achieved with all the EEMs being incorporated in comparison to a combination of four EEMs was less than 12%. The main reason for this is because the combination of all measures together meant adding insulation and glazing simultaneously which did not result in substantial reductions. The energy consumption however benefits the most from the incorporation of all the measures.

Nonetheless, reaching the nZEB target without improving the insulation and/or glazing is not possible. The implementation of insulation/glazing provides a necessary reduction in the space heating demand of the building. Although improving HVAC/DHW equipment individually contributed to significant reductions for all three indicators, when combined with other EEMs their contribution subsides. This, in addition to their energy-cost-saving balance, presented earlier, suggests that improving HVAC/DHW equipment should be one of the final solutions to consider after all other options have been explored.



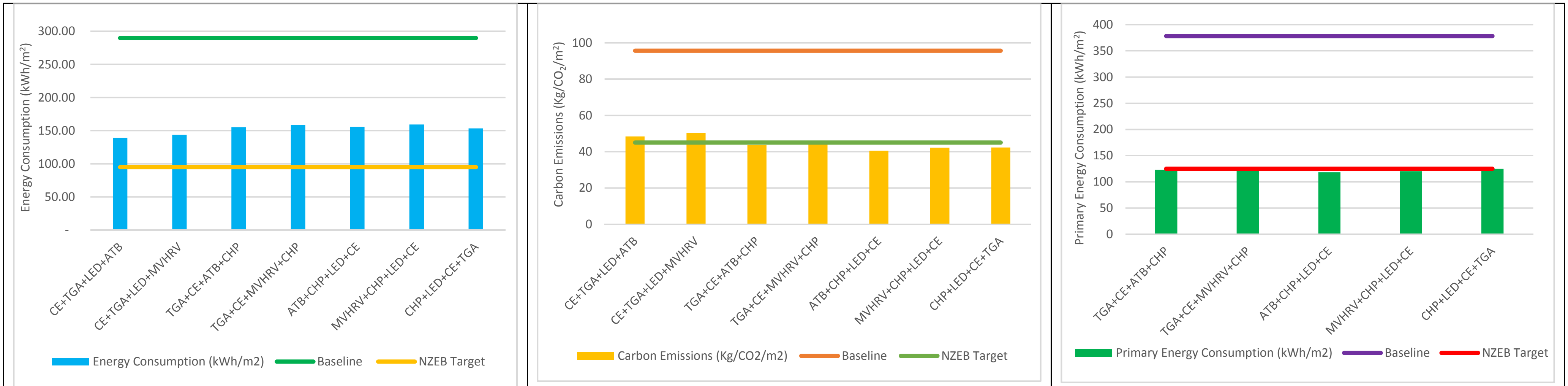
(5a)	(5b)	(5c)

Figure 5: (a) Energy consumption **(b)** Carbon emissions and **(c)** primary energy consumption with a combination of 2 EEMs against baseline model and NZEB target.



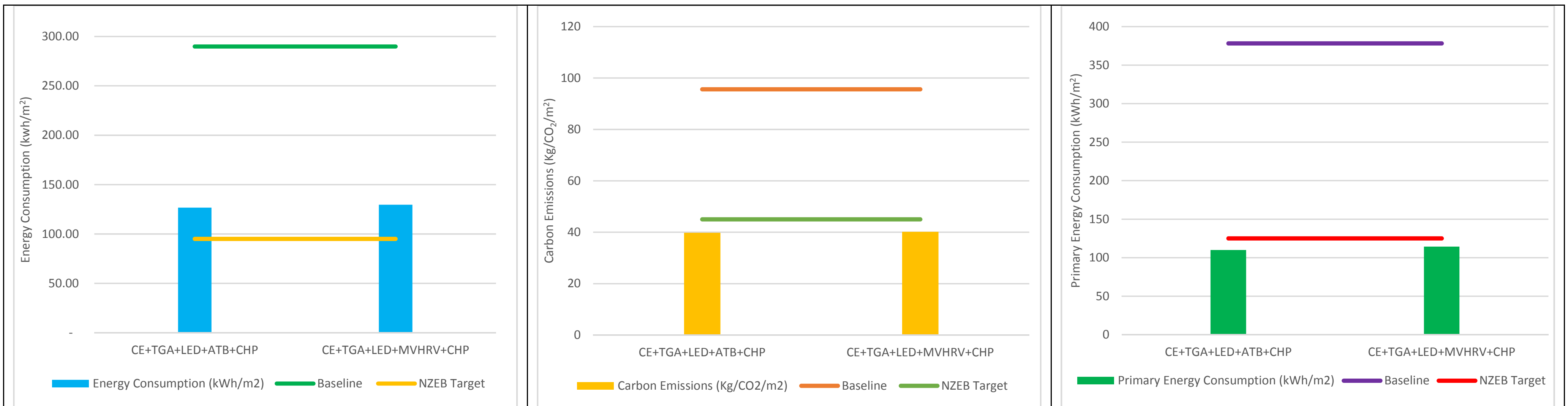
(6a)	(6b)	(6c)

Figure 6: (a) Energy consumption **(b)** Carbon emissions and **(c)** primary energy consumption with a combination of 3 EEMs against baseline model and NZEB target.



(7a)	(7b)	(7c)

Figure 7: (a) Energy consumption **(b)** Carbon emissions and **(c)** primary energy consumption with a combination of 4 of EEMs against baseline model and NZEB target.



(8a)	(8b)	(8c)

Figure 8: (a) Energy consumption **(b)** Carbon emissions and **(c)** primary energy consumption with a combination of 5 EEMs against baseline model and NZEB target.

5. Conclusion

This paper presented the application of dynamic thermal analysis simulation to evaluate the energy performance of Hilton Edinburgh Grosvenor hotel and whether reaching the nZEB standard is feasible for older buildings. TAS was utilised to complete a reliable and accurate baseline model which was validated by comparing against the building's actual performance and obtaining a performance gap less than 5%. The evaluation then considered the effect of individually implementing various EEMs. Once the final selection of EEMs was decided upon based on the initial results, the EEMs were systematically combined to see which combination of EEMs work best together and lower the energy consumption, CO_2 emissions, and PEC to meet the nZEB target. The absence of an official definition for UK nZEBs meant that a different approach needed to be taken to come up with a target that is numerical and specific to UK commercial nZEBs. Hence, the definition was aggregated based on existing successful UK nZEBs, using the data tool developed by the zebra2020 project.

Examining the impact of incorporating different EEMs made it apparent that certain measures have a larger impact on the energy performance of the building. Thus, the following conclusions can be drawn:

To achieve the nZEB standard a combination of at least four EEMs are required. Most importantly, a renewable or microgeneration measure must be one of those measures.

nZEB energy performance is achievable with low and high levels of insulation. The average energy consumption reduction with triple glazing and insulation was 7% and 13%, respectively. Similarly, triple glazing is not necessary to meet the nZEB energy performance target. However, these measures are necessary because they were able to reduce the energy demand by an average of 15% and greatly improve the air tightness of the building. Therefore, not improving the building envelope and heat resistance of building element to lower U-values where there is room for potential improvements will mean the building is not a truly energy efficient nZEB building. However, to obtain maximum savings insulation and glazing should not both be upgraded simultaneously. Instead, based on the existing building fabric and elements of the building envelope either insulation or glazing should be improved. This is particularly true for commercial buildings which tend to be retrofitted more often to ensure occupant comfort and therefore usually already have adequate insulation or glazing.

Improving and/or installing DHW/HVAC equipment does yield significant energy savings, however the cost-savings were very minor in comparison, largely because of the high initial investment cost associated with such measures. In addition, whilst the implementation of insulation/glazing provides a necessary reduction in the space heating demand of the building, incorporating HVAC/DHW measures simply optimises energy consumption. The exception to this is where the measure being incorporated is a renewable measure such as SWH or an air/ground source heat pump. However, these measures underperformed when compared to the microgeneration systems.

It should be noted that recent fluctuations in weather conditions and unprecedented extremes does not only refer to colder weather conditions, but also increased number of heatwaves. In this case the focus on improving the building envelope and its components may prove to be counter-intuitive and increase risk of overheating. Therefore, whilst thermal comfort may be achieved during colder months, it is also possible that during the hotter months overheating and thermal discomfort occurs. Under these uncertain weather conditions, investing in improving HVAC equipment and artificially achieving a balance between the heating and cooling energy needs may prove to be the best solution. For instance, the automatic thermostat gas fired boiler alone contributed to a 27.36% reduction in energy consumption and a 14% reduction for CO_2 emissions.

To ensure lighting related energy consumption is optimised in a cost-effective way, an automatic presence detector is a viable solution. Although these can only be used in certain public areas of hotels to ensure occupant comfort, they have significant energy and cost savings. Furthermore, they worked very well to reduce the energy consumption and CO_2 emissions when combined with any other measures. The true potential of this measure however may only be realised in a different application such as an office or educational building type where they can be utilised in most areas.

Overall, it is clear that the nZEB standard can indeed be achieved for older UK hotel buildings. Based on the results it can be concluded that prioritising improving the energy efficiency of the building and then adding a renewable/microgeneration system to the building is the best approach to retrofit a building located in a cold-dominant climate. In this way the thermal losses because of an energy inefficient building envelope is lowered which in turn drastically lowers the energy demand of the building. This is in consonance with the requirements set by the EU directive which stipulates that nZEB buildings are to have 'very low energy needs.' Thereafter, the incorporation of a renewable/microgeneration measure will then act as an additional provision to finally lower the energy consumption, PEC and CO_2 emissions to meet the standard.

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